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Biofuel production: Prospects, challenges and feedstock in Australia

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ABSTRACT

The growing demands for energy coupled with ever increasing environmental concerns have allowed the global production of biofuels to rise significantly in recent years. Many countries across the world have begun utilising biofuels on a national scale, while many more are in the process of planning and implementing similar steps. While Australia has an abundance of fossil fuels in the form of coal, natural gas, and oil, and currently employs a variety of alternative energy sources, the technology to produce and implement biofuels in Australia is in its embryonic stage. Today, Australia is using first generation feedstock as the main source for the production of biofuel, but is progressively broadening into second-generation biofuel production technology. Australia has an enormous amount of biomass available in the form of agricultural and forestry residues, bagasse and feedstock currently unused for the production of biofuels. The technology for the conversion of lignocellulosic biomass into biofuels warrants further research to maximise yield to the point of industrial feasibility. This review discusses the current state of ethanol production in Australia, the key technological challenges involved in the production of second-generation biofuel and the availability of various kinds of lignocellulosic biomass for biofuel production.

Contents

1. Introduction

The growth of the transport, energy and industrial sectors has led to ever increasing pressure on the availability and cost of fossil fuels. An increase in academic as well as public awareness of global warming and consequences of greenhouse gas (GHG) emissions have further contributed to the search for alternative sources of energy [1,2]. Biofuel, being any fuel made from organic matter resulting from agriculture or forestry, is a multiple objective sustainable resource, promising to substitute fossil fuels with energy from agricultural sources while providing a range of other benefits [3]. However, the complete dependence of first generation biofuels on food crops (such as corn, sugarcane, and wheat) made it somewhat unpopular as it competes directly with the food supply [4–6]. Concerns for dependence on food crops could be settled if biofuels could instead be produced from agricultural wastes, forest residues and organic wastes, a concept dubbed as *second generation* biofuel. Second generation biofuels involve the production of ethanol from lignocellulosic biomass (LCB); a particularly promising prospect due to both the wide-spread availability and high energy density of lignocellulosic

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matter. Bioethanol from lignocellulose is a carbon-neutral, renewable source of energy. Apart from the energy security and environmental benefits from bioethanol production of this kind, it also stands to generate an additional source of income for the Australian rural sector [7].

Biofuel can help to reduce waste as well as providing a source of fuel. As second generation biofuel technologies advance, it will become a preferable source of energy to both first generation biofuel and fossil fuels, because of its wide range of secondary benefits. Second generation biofuel does not depend on a particular feedstock and does not require highly fertile land for agriculture. As biofuels begin to enjoy growing acceptance around the world and in international markets, they could alleviate problems of energy supply while simultaneously helping to mitigate GHG emissions.

The blend concentration of biofuel in diesel and other fuels varies globally. 2%, 5%, 20% and 100% concentrations of biodiesel are among the most typical, marketed in the form of B2, B5, B20 and B100 blends respectively, whereas ethanol is commonly blended with petrol in concentrations of 15% and 85%, respectively marketed as E10 and E85, the latter can be used in dual-fuel automobiles [8]. The recent increase in demand for ethanol provides a large platform for investment, this is especially evident in the growing investor interest in global leaders of biofuel development and use [5], namely the US, Brazil, Germany, Sweden, and France. China, Russia and India are also heavily promoting biofuel production, citing ecological viability, energy security, energy balance, employment and the development of rural sectors and economy. The US and Brazil together produce 78% of the world's fuel ethanol. Brazil uses 25% ethanol blend petrol for transportation [9]. The popularity and production of biofuel varies extensively worldwide, with some nations having developed technologies whereas others are only beginning to realise its potential [10,11]. The Australian biofuels market is currently in the development stage, with the government and private entities engaging in promotion of the technology across the country. Currently E5, E10, E15 and E85 are available throughout Australia as forms of unleaded petrol [12,13]. Regional development and growing awareness and severity of environmental issues have led to a national shift toward viewing biofuels as a potential solution.

National apprehensiveness towards a future where first generation crops are chosen as either food or fuel can be eased by the impending research on second-generation fuel produced from lignocellulosic biomass (LCB). Although the production of LCB ethanol has various technological and economical constraints, it is a sustainable fuel in the long term [14]. The process of converting biomass into biofuel presents an array of technological challenges. The cost of biofuel depends largely on the feedstock, geographical location and the industrial processes employed. Greenhouse gas (GHG) balancing depends on the feedstock used for the production of biofuel; not all feedstock is carbon neutral [15]. The selection of feedstock, its pre-treatment, enzymatic saccharification and fermentation are known to be the key processes involved in the production of biofuel. The pre-treatment of biomass is among the most critical process in the production of biofuel, because the effectiveness of the pre-treatment step dictates the yield of fermentable sugars, and ultimately the ethanol yield [16,17]. Although the cost of biomass substrates is low, the production costs weigh significantly on the ultimate price of biofuel. Advancements in pre-treatment procedures to alleviate production costs are therefore crucial to the economic viability of the technology. Australia has a considerable amount of untapped carbon-neutral biomass, which has not been fully utilised due to the lack of adequate, cost-effective processing technology [18]. The analysis of potential feedstock resource regions in Australia will aid in finding feasible locations for commercial biofuels production facilities [19]. This article focuses on the current status of bioethanol production in Australia, available feedstocks and production challenges.

2. Current status of bioethanol in Australia with respect to global developments

Brazil and the US are global leaders in the production of biofuels from corn, sugarcane and lignocellulosic crops [20]. Production of bioethanol in Brazil, currently at an annual 27 billion litres (GL), has been supported by the development of new sugarcane varieties and agriculture technologies [21]. Bioethanol produced from corn and grain, and biodiesel produced from soybean are used widely as alternatives to fossil fuel (FF) in the US [22]. The US is aiming to replace 30% of its fossil fuel with biofuel while Europe is aiming for 5.75% [23]. Germany is a key producer of biodiesel in the European Union, supporting around 25 biodiesel plants. Exemptions from excise duty for pure and blended biodiesel have made biofuels exceedingly competitive against fossil fuels in Germany [24]. The Federal government in Australia aimed to support 350 million litres (ML) of biofuel production per year from 2010 [25] and the pricing for biofuel is estimated to fall by as much as 12.5 c/L for ethanol and 19.1 c/L for biodiesel by 2015 [26].

Countries in Asia are also emerging players in the biofuels market. Among them, China produces an enormous amount of agricultural residue suitable for biofuel production, with ethanol blended fossil fuel comprising 20% of total Chinese petroleum consumption [27,28]. In India, first generation biofuel technology is more mature than second-generation technologies, with India supporting its bioethanol production with sugarcane molasses and biodiesel from *Jatropha* [29,30]. In Southeast Asian countries such as Malaysia, Indonesia and Thailand, the production of biodiesel is primarily from palm oil and *Jatropha*. Thailand produces its ethanol from cassava and sugarcane, and is investing in the commercialisation of B5 and B10, aiming to make it available throughout Thailand by 2012 [31]. Several Asian countries are also growing *Miscanthus* for fibre and pulp production, although by 2020 biofuel production is set to become its primary use. The US has also planned to cultivate switchgrass for biofuel production over several million hectares, and has established a renewable fuel standard that enforces a mandatory minimum annual production of biofuel and a mandatory fraction of second generation biofuels in its overall production volume [32].

Australia also produces large amounts of biomass from forest plantations, agricultural residues and organic wastes used in the production of bioenergy, mainly electricity. A considerable amount of renewable energy is produced annually, contributing significantly towards the primary energy production of Australia (Table 1). Nevertheless, the production of biofuel on a commercial scale using available biomass requires mature technology and experience. The production cost of ethanol depends strongly on both availability and productivity of different kinds of biomass as well as the chosen production strategy. Australia produces less than 5% of its energy from biomass [33]. The resources for the production of bioenergy (electricity and biofuels) come primarily from the sugar, wood processing and paper manufacturing industries [34]. The production of second-generation biofuel is currently in its infancy. Similarly, Brazil began refining biofuels in 1970s as it experienced high oil prices and it produces biofuel from sugarcane in the late 1920s. Brazil invested in the erection of biofuel distilleries to produce a 20% blend across the country [35].

The production of second-generation biofuel from sugar production wastes and agricultural biomass is currently in the

Table 1
Australian production of renewable energy.

Renewable Energy	2002–03 pJ	2003–04 pJ	2004–05 pJ	2005–06 pJ	2006–07 pJ	2007–08 pJ	2008–09
Bagasse	95.1	101.1	108.3	109.1	110.8	111.9	110.1
Biogas and Biofuels	10.7	10.1	8.7	9.4	10.2	17.6	23.8
Hydroelectricity	59.4	58.8	56.2	57.7	52.3	43.4	44.3
Solar electricity	0.2	0.3	0.3	0.4	0.4	0.4	0.6
Wind	0.6	1.6	3.2	6.2	9.4	11.1	13.7
Wood and Wood waste	105.3	97.3	91.5	90.3	92.8	96.0	102.0

The petajoule (pJ) is equal to 10^{15} J.
This table has been modified from reference [125].

Table 2
Australian energy consumption in recent years.

	2003–04 pJ	2004–05 pJ	2005–06 pJ	2006–07 pJ	2007–08 pJ	2008–09 pJ
Black coal	1578	1618	1639	1686	1701	1612
Liquid biofuels	1	1	1	2	5	8
Wood, wood waste	97	92	90	93	96	102
Bagasse	101	108	109	111	112	110
Petroleum products	1885	1945	1969	1990	2036	110
Natural gas	1066	1052	1078	1195	1262	1250

The table has been modified from references [124] and [125].

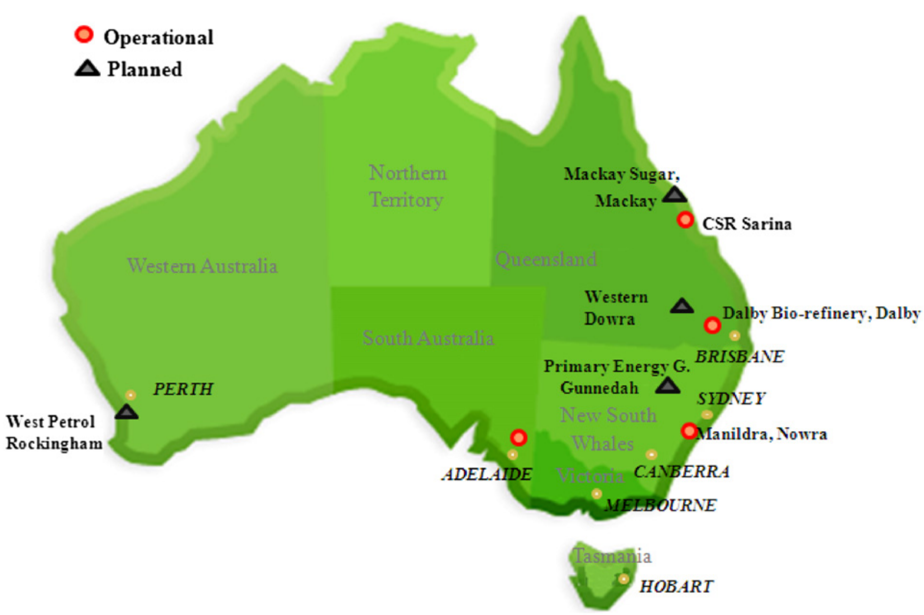

Fig. 1. Location and status of Australian ethanol project.
Source: This figure has been modified from APAC biofuel Consultants, 2009 [123].

development phase in Australia. In the past five years, Australia has seen a significant increase in biofuel consumption (Table 2). Three major bioethanol facilities are currently in operation in Australia: The Manildra facility in Nowra, New South Whales, Australia's largest bioethanol producer, followed by the Sarina distillery and the Dalby bio-refineries in Queensland [36]. The Manildra Group is the largest commercial ethanol producer in Australia, and is planning to upgrade its production capacity from 126 ML per year to 300 ML per year to meet a New South Wales government mandate to blend 2% ethanol in the total volume of petrol by 2011 [37]. The Colonial Sugar Refining (CSR)–Sarina distillery has been awarded AUD$13 million to upgrade its ethanol production from 38 ML to 60 ML per year [38]. An investment of AUD$115 million has been made towards the construction and development of the Dalby bio-refinery in Queensland for ethanol production from sorghum and sugarcane [39,40]. The current operational and various planned ethanol production locations in Australia are shown in Fig. 1.

The State of Queensland produces around 120 ML of ethanol per year from first generation feedstock, such as sugar and grain, a figure expected to increase in the future [4,41,126]. The Queensland government invested AUD$3.6 million in biofuel research in 2010, of which AUD$2 million was invested in the "Queensland Sustainable Aviation Fuel Initiative" to produce biofuel from sugarcane bagasse, oilseed trees and algae, and AUD$1.5 million in the production of a low cost, high productive photo-bioreactor to grow algae for biofuel production under the "High Efficiency Microalgal Biofuel System Project". The State of Victoria is in its

initial stages of producing bioethanol from cereals such as wheat and barley [42]. The Victorian government recently signed a memorandum to build a consortium of companies to produce an annual 200 ML of ethanol [43]. Victoria has a facility to support bioenergy production and waste-water treatment through supercritical water gasification, which provides product selectivity by altering the conditions to obtain the desired products, for example, low temperature to produce natural gas and high temperature to help in developing fuel cell technology [44].

Sucrogen bioethanol (a division of CSR Limited) is one of the major bioethanol producers in Australia, producing 60 ML of ethanol per year from the molasses supplied to the food and beverage sector, the industrial market and the fuel market [45]. "Satake Australia" in New South Wales, is planning to produce Australia's largest bioethanol plant utilizing cereals. It currently produces over 100 million gallons of ethanol per year from maize. Using the company's PeriTecDebranning Technology, Satake Australia are maximising the fermentable product from wheat, barley and sorghum [46]. Due to the 34% increase in demand for biofuel from 2008 to 2009 in Australia, the expected demand for biofuel in 2010 was estimated at 636 ML, a figure further expected to more than double to around 1.5 GL by 2015 [47]. Australian production of biofuel in 2009 from various biomass sources is illustrated in Table 3.

Two bioethanol products, EGEN-95 and EGEN-98, have been launched by the Neumann Group located in Queensland and New South Wales, comprising a 10% ethanol-enriched blend with octane ratings of 95 and 98 respectively [48]. CSR is expending around AUD$17.8 million to produce fuel-grade ethanol products such as E10 and E85 [50]. In contrast, in 2010, Caltex Australia launched a high ethanol blend fuel, Bio E-Flex (E85), with 85% of the ethanol produced being from first generation feedstock. It produces Bio E10 using waste starch from the processing of wheat, and molasses from the sugarcane and sorghum that are grown for ethanol production. Apart from bioethanol, Caltex Australia produces Bio B5 and Bio B20 biodiesel, constituting 5% and 20% biodiesel respectively, produced from used cooking oil and animal fats (tallow) [49,50]. BP Australia began marketing E10 fuel in 2001 in Queensland, and is now aiming to produce 400 ML of biofuel per year, exceeding the target of the Federal Government. BP's new plant in Kwinana, Western Australia is using 200,000 t of wheat as feedstock to produce renewable fuel (E10) and electricity [51,52]. In Western Australia, Primary Energy Pty. Ltd. is currently establishing a grain based ethanol plant with the capacity to produce 500,000 L of ethanol per day [53].

Australia as a country is on her way to understanding how its feedstock can be used for biofuel, and to resolve the challenges involved in its production. To this end, the Federal and State Governments are reinforcing biofuel by providing various grants and schemes to support biofuel production with tax exemptions and excise advantages [54]. The Federal Government has recently established a "Clean Energy Finance Corporation" which will invest AUD$10 billion in developing renewable energy, and low-pollution and energy efficient technologies [55]. Similarly, in order to support biodiesel production, the European Commission (EC) has established national standards to improve engine quality and engine compatibility with various fuel blends, whereas the US and Canada have established demonstration units and commercial ventures for bioethanol production processes [56]. Ethanol blend fuels have been shown to produce a lower concentration of GHG than fossil fuel, proving to be a superior, more sustainable fuel in the long term and thus encouraging the introduction of even more blend combinations to the market [57] and increased pressure on the need for more production plants to produce renewable fuels.

3. Technological challenges: production of bioethanol

Biomass is a great reserve of carbon which, if utilized in an efficient way, can also help to mitigate the global energy crisis. A vast amount of biomass is available worldwide, contributing 14% of global final energy consumption [58]. The utilization of biomass by a bioconversion process will (i) solve the disposal problem, (ii) reduce the cost of waste treatment, and most importantly (iii) produce an alternative to fossil fuels [59]. Most waste agricultural residues are burned in the field, ultimately causing environmental problems and destroying nutrients.

LCB for biofuel production can be obtained from agricultural sources, waste materials, forest wood such as softwood or hardwood and grasses [60]. LCB is mainly composed of lignin, cellulose and hemicellulose; other components present in lignocellulose are pectin, wax, proteins, and ash [61–63]. These polymers are highly coiled and enmeshed by non-covalent forces and covalent cross-linkage, making them difficult to hydrolyse into small fragments. Therefore, to make cellulose accessible for enzymatic saccharification, an effective pre-treatment is required. This in turn poses a further series of challenges [64]. The basic aim in the conversion of feedstock to biofuel is to eliminate oxygen from carbohydrates to obtain hydrocarbons; the energy content of the biomass increases with the decrease in oxygen

Table 3
List of Biofuels production facilities in Australia.

Location	Capacity (ML/yr)	Feedstock
Fuel ethanol		
Manildra Group, Nowra, NSW	180	Waste wheat starch, some low grade grain
CSR Distilleries, Sarina, Qld (North Qld)	60	Molasses
Dalby Biorefinery, Dalby, Qld	90	Sorghum
Biodiesel (in production)		
Biodiesel Industries Australia, Maitland, NSW	15	Used cooking oil, vegetable oil
Biodiesel Producers Limited, Wodonga, Vic	60	Tallow, used cooking oil
Smorgon fuels, Melbourne, Vic	100	Dryland juncea (oilseed crop), tallow, used cooking oil, vegetable oil
Various small producers	5	Used cooking oil, tallow, industrial waste, oilseeds
Australian Renewable Fuels, Adelaide, SA	45	Tallow
Australian Renewable Fuels, Picton, WA	45	Tallow
Not in production		
Eco-tech Biodiesel, Narangba, Qld	30	Tallow, used cooking oil
Vopak, Darwin, NT	130	Palm oil

This table has been modified from references [124–126].

content [65]. The size reduction of the biomass is a preliminary step prior pre-treatment, and is done to reduce cellulose crystallinity and to increase particulate surface area and therefore digestibility [66]. The energy required for a significant reduction in size of biomass particles is one of the factors contributing to the high production costs [67]. The selection of an effective pre-treatment method following size reduction is a major challenge and of some concern because the enzymatic hydrolysis and ethanol yield will be dependent upon the quality of this step [68]. The enzymatic hydrolysis of the biomass has proved to be less convenient than high temperature acidic treatment, as the latter leads to the formation of degradation products such as 5-hydroxymethyl-2-furaldehyde (HMF) especially in softwoods, which directly influences sugar yield and ethanol production; the yield of the sugar and the by-product depend on the hydrolysis conditions [69–71]. The final step in the bioconversion process is the fermentation of the sugar produced by enzymatic hydrolysis, which is generally done by using *Saccharomyces cerevisiae* (Baker's yeast) or the bacterium *Zymomonas* sp. Many other challenges are also encountered during the conversion process, such as the variation in pH, hindrance by ions and metals, and hydrolysis of by-products such as acetic acid, formic acid, and levulinic acid which interfere with the ethanol yield and its volumetric productivity.

To overcome these limitations, there is a pressing need for a mature technology that can enhance efficiency and productivity in an economical way. Cost analysis at each step is essential to determine the feasibility of the entire strategy in terms of productivity and return on investment. More focus must be given to upstream processing, as this is an important function in determining the success of ethanol production on a commercial scale [72].

4. Pre-treatment of biomass

The objective of pre-treatment is to degrade the structure of the lignocellulose by removing lignin and hemicelluloses and providing a surface area for enzymatic hydrolysis through exposing of the cellulose [73].The cross-linkage between lignin and the polysaccharides, such as cellulose and hemicellulose with ester and ether, makes the biomass structure hardwearing and robust. An effective pre-treatment is required to break the compact packing of bonds in the biomass, thereby making cellulose accessible for the production of pentose and hexose sugars [74]. There are numerous technological trends and advanced strategies being followed across the world to best enable hydrolysis of biomass. The methods used for hydrolysis can broadly be classified as physical (milling and grinding), physicochemical (steam explosion, oxidation), chemical (alkali, concentrated/dilute acid, oxidizing agent and organic solvents), biological, or a combination of the three [75]. However, the most challenging part is to identify an economic and high ethanol yielding strategy that can be used on a commercial scale. This requires extensive research and knowledge to produce a highly technological pathway that optimises energy consumption in biofuel production [76].

Physical pre-treatment is the preliminary step included in almost all pre-treatment techniques. Mechanical comminution involves milling, grinding or chipping which is basically done to reduce the size of the wood chip to facilitate the breaking of cellulose crystallinity. A wide range of chip sizes are used for pre-treatment (300–1400 μm, 2–12 mm or higher) [77]. Usually, a small size results in the most efficient hydrolysis, but reaching such small sizes also consumes more energy. In addition to the size of wood chip, the duration of the pre-treatment also affects the hydrolysis of the biomass. The efficiency of the hydrolysis is determined by the amount of cellulose converted into monomers by the action of enzymes, hemicellulose solubilisation, the recovery of cellulose and hemicellulose, the atomic ratio, and crystallinity, all of which decide the efficiency of the pre-treatment technique [78].

Pyrolysis is a process which hydrolyses polysaccharides with heat in the absence of oxygen; it forms volatiles, chars and gaseous fractions in the reaction at temperatures ranging from 259 to 341 °C [79,80]. This process assists in studying the thermal behaviour of lignin through intermediate and final products; the reaction takes place via a free radical mechanism and the addition of salt to the reaction brings about weight loss in the reaction mixture while metals enhance the biomass hydrolysis [81]. Steam explosion is a pre-treatment technique that increases the pore volume of the biomass by degrading the hemicellulose content that provides a surface area for efficient enzymatic hydrolysis. During this process, temperature is the most significant factor that affects the yield of pre-treated polysaccharide [82,83]. Along with the deterioration of hemicellulose, steam explosion decreases acid soluble lignin while increasing the insoluble lignin content, enhancing the density and thermal stability of the biomass [84]. Ammonia fibre expansion is a process that includes the exposure of lignocellulose to ammonia in order to increase its viability for enzymatic hydrolysis. This process is customised by four parameters: ammonia loading, water loading, reaction temperature and residence time [85]. Ammonia fibre expansion creates a nick in the ester linkage of cell wall by ammonolytic cleavage, releasing acetamides and phenolic amides which are the essential nutrients for downstream processing [86]. Carbon dioxide explosion is another pre-treatment method, whereby supercritical carbon dioxide at varying pressures is used as an extraction solvent. Carbon dioxide is used primarily because it is inexpensive, has a low critical temperature and is non-inflammable, clean and easy to recover after use [87].

Acid hydrolysis is most commonly achieved by using either hydrochloric acid (HCl) or sulphuric acid (H_2SO_4) and an alkaline treatment with lime and sodium hydroxide for the conversion of a biomass into ethanol [88]. Recently, ionic liquid (IL) pre-treatment has been observed to produce a greater surface area for enzymatic hydrolysis, thus increasing crystallinity. ILs decrease the amount of lignin content, which indicates that ionic liquid is more efficient than dilute acid [89]. However, the cost of ionic liquid is of major concern for industrial viability. Degradation of raw material with steam explosion leads to a considerable loss of hemicellulose and when coupled with alkaline hydroxide as a post treatment the content of lignin decreases, with a significant increase in cellulose crystallinity [90].

The major concerns associated with the pre-treatment are: (i) the selection of the pre-treatment strategy, (ii) high energy consumption required to maintain pre-treatment conditions, (iii) economical large scale processing, as the yield of ethanol is influenced by the efficiency of pre-treatment and (iv) the pre-treatment technique should not rely on a particular feedstock; it should be effective for a variety of biomass types.

4.1. Enzymatic saccharification of pre-treated biomass

The biomass is composed of various components that make it a rigid structure, so it requires a group of enzymes or a multi-enzyme complex that can break down pre-treated lignocellulose into fermentable sugars (hexose and pentose), which in turn be easily fermented to biofuel (see Fig. 3). A successful conversion of biomass into biofuel cannot be achieved by pre-treatment alone; the enzymatic saccharification of a pre-treated biomass into sugar is one of the significant steps involved in the conversion process. The efficiency of cellulase determines the saccharification process

that controls the yield of sugar. The cost of the enzyme is another factor that increases the production cost of biofuel because the yield of sugar depends on the enzyme loading.

Cellulase works with the synergistic action of three other enzymes; endo-β-1, 4-glucanase (EG), cellobiohydrolase (CBH), and β-glucosidase. Endo-cellulase/Endo-glucanases (EG) break the non-covalent bonds in a cellulose structure, thus helping to loosen the polymeric crystalline structure and form a linear chain. Exo-cellulase/exo-glucanase (EXG)/cellobiohydrolase (CBH) act on the linear chain to form two to four units of cellobiose which then become hydrolysed by cellobiase/β-D-glucosidase (CB) to produce single glucose units [91]. This reaction system occurs in various steps; (i) transfer of the enzyme from the bulk phase to a cellulose environment, (ii) reaction of the enzyme and substrate to form an enzyme–substrate complex through adsorption, (iii) hydrolysis of cellulose, (iv) transportation of hydrolysed units such as cellodextrin, glucose and cellobiose from cellulosic particles to an aqueous phase, and finally (v) via the action of cellobiase, cellodextrin and cellobiose become hydrolysed in the aqueous phase to form glucose units [92].

Advanced biotechnology and protein engineering modelling can enhance the efficiency of enzymes by immobilizing and constructing a synthetic enzymatic pathway [93]. Cell-free synthetic pathway biotransformation (SyPaB) can contribute to the production of low-cost biofuel by breaking down natural biopolymers. SyPaB is constructed in an in vitro condition and constitutes a number of purified enzymes and coenzymes designed to catalyse a complex reaction [94]. Sometimes, if delignification is not achieved, a huge amount of enzyme loading will be required to hydrolyse a biomass into simple sugars, which indirectly increases the biofuel production cost. Apart from inefficient delignification, some pre-treatment methods and reaction conditions could result in the formation of inhibitors during enzyme saccharification. The occurrences of various inhibitors such as phenolic compounds (4-hydroyxbenzoic acid, syringaldehyde and vanillin), organic acids (acetic, levulinic and, formic acid), cellobiose and, furan derivatives (hydroxymethylfulfural, furfural) during the enzymatic saccharification reduce the sugar yield [95,96]. The inhibition in the product formation occurs due to the solubility of the substrate, the nature of the enzyme complex, enzyme adsorption onto the substrate, the reaction steps involved, and the nature of the active sites on the enzyme [97].

4.2. Microbial fermentation

The ethanol yield also depends on the substrate, utilised bacteria, concentration of enzymes and nutrients, temperature, pH, oxygen supply, and pressure; variation in any of these factors will significantly affect the fermentative production of ethanol [98]. *S. cerevisiae*, *Zymomonas mobilis* and recombinant *Escherichia coli* are commonly used micro-organisms for ethanol production. *S. cerevisiae* uses the Embden–Meyerhof pathway (glycolysis) to produce two molecules of ethanol and ATP from glucose, whereas *Z. mobilis* uses the Entner–Doudoroff pathway to produce the same product with the release of one ATP molecule [99]. Ethanologenic bacteria *E. coli* are now capable of hydrolysing phosphoric acid hydrolysates while other bacteria such as *Bacillus*, *Kliebsiella* and *Clostridium* sp. use the pentose phosphate pathway (PPP) for ethanol production [100,101]. The bioconversion of LCB using solid substrate fermentation enables the production of biofuel, synthetic enzymes, animal feeds, biopesticides, secondary metabolites and biofertilisers as bioproducts [102]. Optimal production of ethanol can be achieved when sugars are completely released and utilised during fermentation [103]. The presence of an inhibitor has different effects on the SSF (simultaneous saccharification and fermentation) and SHF (separate hydrolysis and fermentation) processes. Yeast cells experience various stresses during ethanol fermentation, such as high temperatures, nutrient deficiency, contamination, and inhibitors produced from yeast cell metabolism. These conditions work mostly synergistically, thus affecting the growth of yeast and finally ethanol yield [104].

Continuous fermentation offers advantages over a batch process such as (i) reduced cost for conditioning inhibitory compounds by the in situ detoxification abilities of yeast, (ii) providing higher productivity due to higher cell density, and (iii) reducing viscosity of the substrate [105]. The yield of ethanol during fermentation basically depends upon the capability of the microorganism to convert various sugars (hexose and pentose) efficiently into ethanol and to withstand the inhibitory conditions.

5. Australian feedstock availability

Biomass is available in abundance in Australia and provides a platform for large investment in the biofuels sector. Feedstock in the form of forest plantations, agricultural residues, and organic by-products from industry are widely available (Fig. 2). However, with the adoption of better technology, a vast market for biofuel/bioenergy production has the potential to flourish. In the UK, some types of biomass such as wheat straw, coppice willow, *miscanthus*, sugar beet are popular and have supported biofuel production. The environmental impact of biofuel is the most significant reason for biofuel investment in the UK [106]. Ethanol is produced mainly from molasses, cane juice and raw sugar. African countries too are attempting to produce ethanol from molasses, cane juice and raw sugar. Among them, Zimbabwe pioneered biofuel production whereas other African countries are only in the preliminary stages and yet to make a mark on the world biofuel productions map [107].

The production of bioenergy is an area of interest to the Australian Green-house Office because it can provide energy security for the nation, help in the reduction of carbon dioxide emission from transportation and industry, and largely serve as a potential economic market [108]. Biofuel adds value to biomass in different ways because biomass contains water soluble carbohydrates, water insoluble carbohydrates and hydrocarbons which can be utilised through bioprocessing technology. Biomass plantations provide multiple benefits, such as reducing soil salinity and wind erosion, while providing

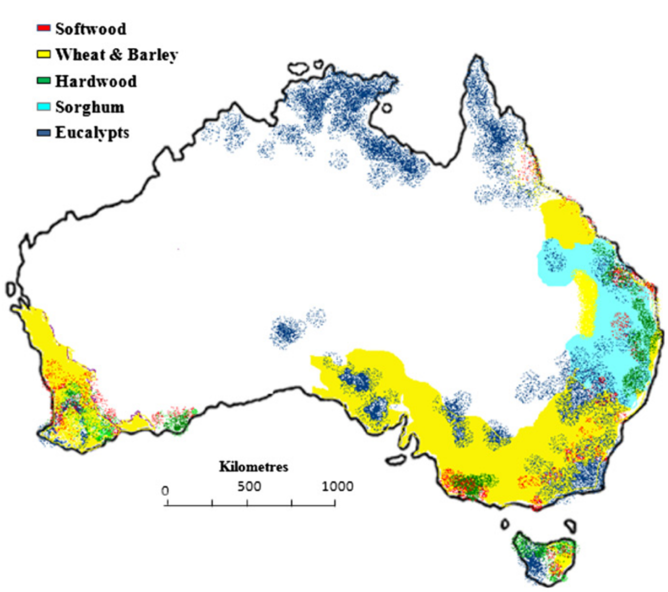

Fig. 2. Biomass location for biofuels production in Australia.
Source: This figure has been modified from National forest inventory [127].

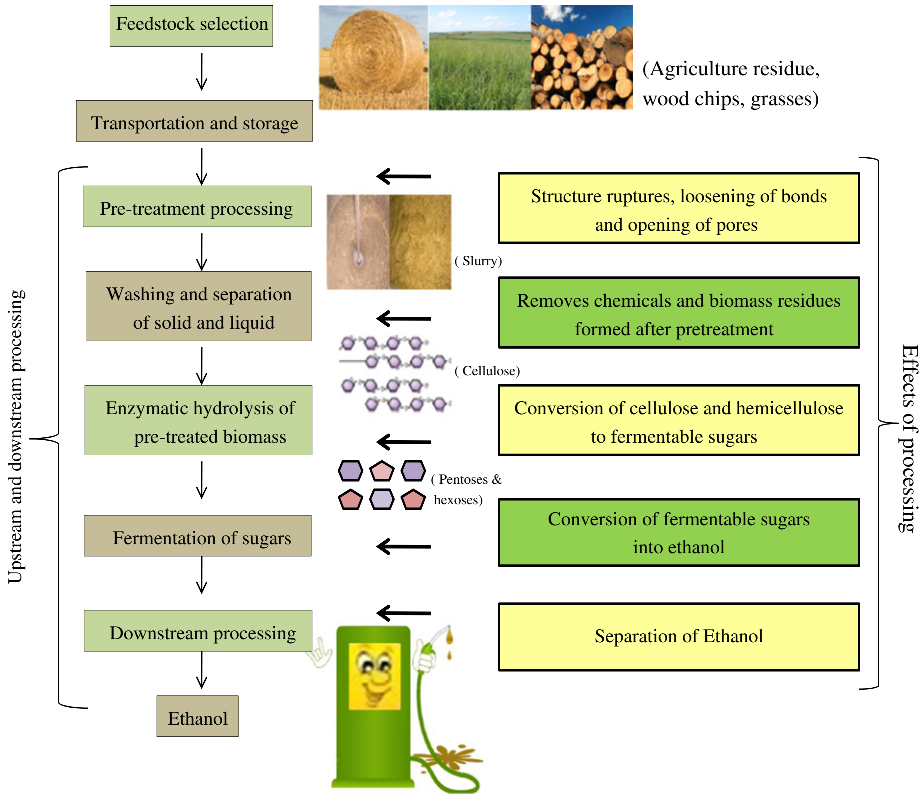

Fig. 3. Flow chart showing the steps in the production of cellulosic ethanol from various feedstock's.

feedstock for biofuel and electricity production and fodder for animals. Australian forest plantations are an important economic market, as they produce two-thirds of the nation's log supply. Around 1.9 Mha of forest plantations are available in Australia, and these are comprised of both hardwood and softwood species such as eucalyptus and pines. The States of Victoria and Western Australia cover around 21% of the plantation, while NSW has 19%, Tasmania 14% and Queensland 13% [109]. Australian forests cover 19% of total Australian land area, which is predominantly open woodland. Forest plantation has increased since the 1990s and the wood supply is expected to rise to 29 million m^3 by 2020 [110]. Bagasse is the largest renewable resource in Australia, used primarily in the production of electricity. Australia produces over 11 million tonnes of bagasse annually and over 9 million tonnes of cane waste, comprising leaves and tops, which have traditionally been burned in the field each year. This could serve as a potential source for the commercial production of biofuel. Forest residue, sugarcane and wood waste will be sufficient to meet the federal government's bioenergy target of producing 1.5 GL of biofuel by 2015 [111]. Similarly, the Indian government has also estimated that around 26.6 Mha of land can be used for biofuel production as it is planning to expand its biofuel sector by blending 10% ethanol with petrol and further substituting 20% of diesel with biodiesel [112].

Eucalyptus is another good source of lignocellulosic biomass, which is widely available in Australia. It is a fast growing hardwood as the Australian climate favours its growth. It is estimated that in 15 years, Australia will be able to produce 10 million tonnes of eucalyptus wood residue from Government and "Managed Invest Schemes" (MIS). Eucalyptus is considered to be a major potential resource for the production of ethanol because it supports the current conversion technology and, in addition, the availability of a large variety can contribute to high productivity [113]. A study conducted by the WA industry illustrates that the plantation of *Eucalyptus* sp. (mallee) between the wheat belts could solve the problem of salinity in the soil by overcoming soil erosion and, in addition, would benefit biomass production [114]. The cultivation of another species of eucalyptus, known as bluegum, has also increased by over 500,000 ha within the past decade. Various woody weeds could also prove to be potential drivers for the production of biofuel, such as *Camphor laurel*, *Mimosa pigra* and *Acacia nilotica*. These weeds are gaining significant importance because of suitable climatic conditions in Australia [115].

Some perennial grasses such as Napier grass (*Pennisetum purpureum*), *Miscanthus* sp. and Giant reed (*Arundo donax*) could also be considered for the production of biofuel in the state of South Australia. A detailed study (growth curve, biomass yield, ethanol production) was carried out on Giant Reed to analyse its potential for commercial scale biofuel production [116]. A perennial pasture (e.g. elephant grass) has enormous prospects for biofuel production. Currently these pastures are left for heavy grazing, burnt or left for decomposition in the field. Other agricultural biomass residues available in Australia that can serve for biofuel production are sorghum, cereal straw and citrus processing waste [26,128]. In addition to agricultural residue, an urban biomass which includes timber waste can also be used for bioenergy production [117].

6. Conclusion

Biofuel production acquired its impetus from the depletion of fossil fuel reserves, the environmental benefits and its availability based on biomass abundance. The rising price of fuel, the increasing concern over global warming and the lack of competition from food crops also favoured the production of biofuel from

the lignocellulosic biomass. With the help of advanced bioprocessing technology, agricultural wastes can be successfully hydrolysed and converted into useful bio-products such as transportation fuels, nitrate and nitrogen removal from water, removal of heavy metals and dyes from aqueous solutions, and the production of electricity. Numerous methods are practised worldwide, aiming to develop better pathways for the conversion of biomass into high yield ethanol, butanol and other improved alcohols. The development of the biofuel sector is set to raise the price and demand for feedstock because of its extensive requirement in biofuel production, along with other factors such as competition for land between non-food crops and food crops, irrigation, and nutrition [118]. Currently the technologies are not mature enough to prove their competitiveness against fossil fuel, because of high production costs. However, in the near future, biofuel will emerge as a giant in the fuel industry, as it will support the reduction of greenhouse gases while providing a politically stable, renewable and ultimately cost-effective alternative to the fuels typically employed by countries today.

The production of bioethanol is cheaper in Brazil in comparison to the US and Europe, due to production technology, labour and transportation cost. Brazil began marketing 20 to 25% ethanol blend gasoline in 1993, and currently more than 80% of their automobiles are flex-fuel vehicles. Likewise, the US is endorsing ethanol blend E85 and has set a target of producing 28.4 GL of bioethanol by 2012 [119]. Australia is making significant strides in advancing confidence in biofuel products as well as expanding its distribution network. The gap in the confidence of stakeholders and production of biofuel is basically due to lack of common support and view for a particular production [120]. The Planning Commission of India, which had the capacity to produce 2.9 GL in 2003, has planned to produce 3.8 GL of ethanol from molasses and cane by 2017. India is forecasting a shift to other crops like sorghum and sugar beet as well as the traditional use of surgarcane molasses [121]. Australia is already blessed with a range of feedstocks, demanding only the implementation of efficient bioprocessing plants to produce bioethanol on a commercial scale, to which it can look to the success stories of the BRIC (Brazil, Russia, India and China) countries.

The incumbent Australian federal government, through the Department of Resources, Energy and Tourism has intensified research on biofuel production by investing AUD$5.1 billion over the coming decade as part of their "Clean Energy Initiative" for supporting research and development into new renewable energy technologies [122]. A significant victory for the biofuel production industry in growing confidence of stakeholders will expand the biofuel market significantly in Australia, as many automobiles compatible with low blend and high blend biofuel are already available, pending only wider implementation of the technology.

Biofuel is a new market for the agriculture sector, as it provides potential opportunities for rural and regional community development, as well as supporting urban communities, improving air quality and health in cities and most importantly providing a buffer against rising fuel prices. Reinvigorating rural Australian industry and reducing environmental problems will bring an overall change in the outlook for biofuels, further driving its popularity among every day Australians. There is a tremendous opportunity in-waiting to transform Australian agriculture, particularly from forestry biomass, into a 'bio-economy', heralding a biofuel generation across the nation.

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